XIV. Advanced Projects Development

ENGINEERING MECHANICS DIVISION

A. TOPS Mechanical Devices, *E. E. Sabelman*

1. RTG and Science Boom Actuator–Damper

a. Introduction. A torsion rod actuator and concentric rotating tube viscous damper have been proposed for deployment of the thermoelectric outer planet spacecraft (TOPS) radioisotope thermoelectric generator (RTG) and science booms (SPS 37-60, Vol. III, pp. 177–179). This combination is advantageous because the damper tubes replace a compression member between the hinges of the rigid boom to minimize the weight penalty (Fig. 1).

In the present TOPS configuration, 12L, the RTG assembly weighs 114 kg and its center of mass is 2.46 m from the boom hinge axis. The RTG boom must deploy through an angle of 70 deg, with minimum perturbation of spacecraft attitude and minimum residual velocity at latching.

A test model has been constructed to verify the deployment characteristics predicted by the analog computer program (SPS 37-60, Vol. III) by full-scale simulation of the mass and moment arm of the RTG boom. The test setup has also been used to develop methods of low-friction deployment testing suitable for a flight-type spacecraft.

b. Actuator–damper test model. For fabrication reasons, the test model damper (Fig. 2) was shortened to 23 cm, half of the full-scale length. To preserve the same total shear area and thus the damping coefficient, a third tube was added, doubling the number of shear surfaces. The outer tube has a 2½-in. OD, a 0.035-in. wall, with a 0.012-in. nominal fluid film thickness. Using a one million centistoke silicone fluid, the net damping coefficient is 10^9 dyne-cm/(rad/s) [850 in.-lb/(rad/s)].

The torsion rod in the test model is full length, and is adjustable in preload by means of an indexing hub and pin on the rotating end. Rods 3/16 in. in diameter of 2024 aluminum and of 4340 heat-treated steel have been tested to date. The bearings on which the boom rotates are dry lubricated Acme threads cut into the aluminum hinge

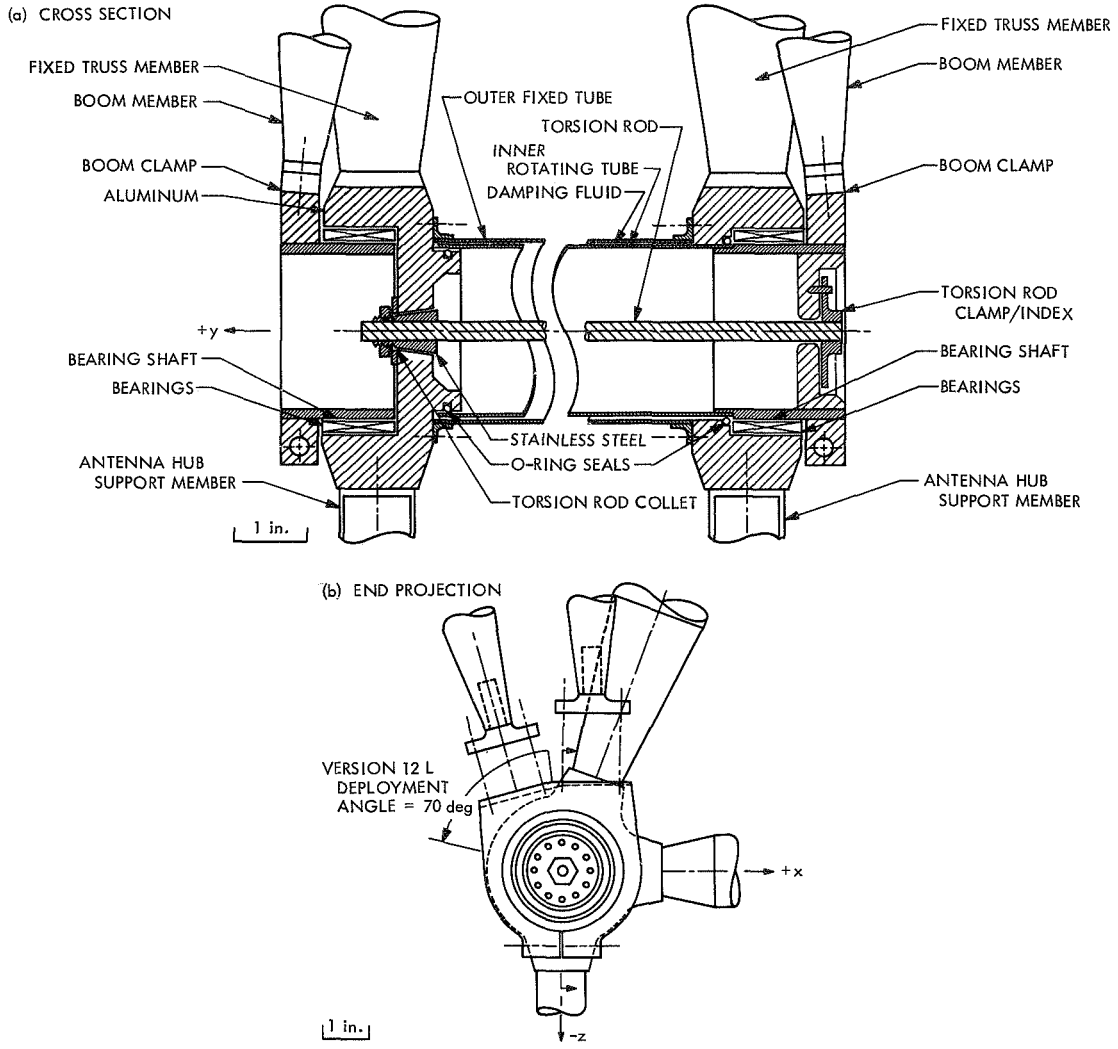

Fig. 1. Cross section and end projection of TOPS RTG actuator–damper

halves; this provides a labyrinth seal for the damping fluid, although O-ring seals would be used on a flight-type device.

c. RTG simulator and low-friction support. The RTG mass is modeled by an appropriate number of lead bricks (Fig. 3). Minimal friction has been achieved by supporting the pallet of bricks on a 10-in.-diameter "Airfloat" air bearing. The bearing travels through an angle up to 100 deg on a circular track of ¾-in. plywood, covered with polyethylene sheeting, and supported by 42 leveling screws.

d. Test procedures. Most of the test runs were made to the TOPS version 12J requirements (RTG mass 100 kg at 1.95 m and 78-deg deployment angle). Because the moment of the simulated RTG is very large compared with the actuator torque, it is quite important that the air-bearing support track is accurately leveled. The procedure for doing this is to first use a spirit level, then decouple the air-bearing pallet from the actuator–damper and use this as a much more sensitive indicator. (A thicker honeycomb sandwich construction would overcome difficulties in flexibility and unevenness of joints encountered with the plywood track.)

Testing is then initiated, with zero preload on the torsion rod and a reduced RTG mass. The mass is increased until critical damping is reached and the preload is increased if required to reach the zero angle (lock-open) point.

e. Test results. Performance of the damper has been as expected, but the available torque output and zero point

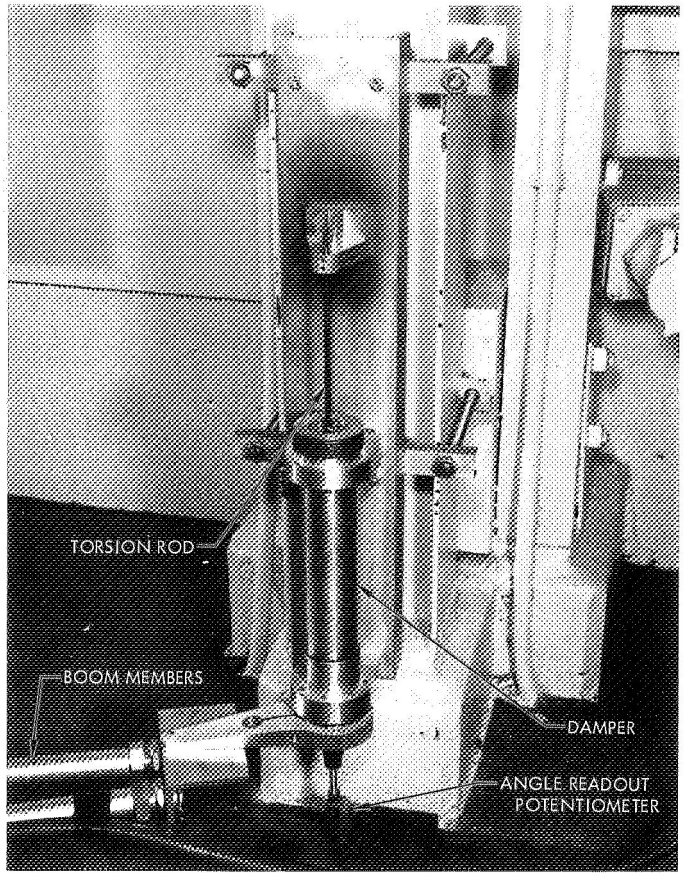

Fig. 2. Actuator–damper test model (half-length damper)

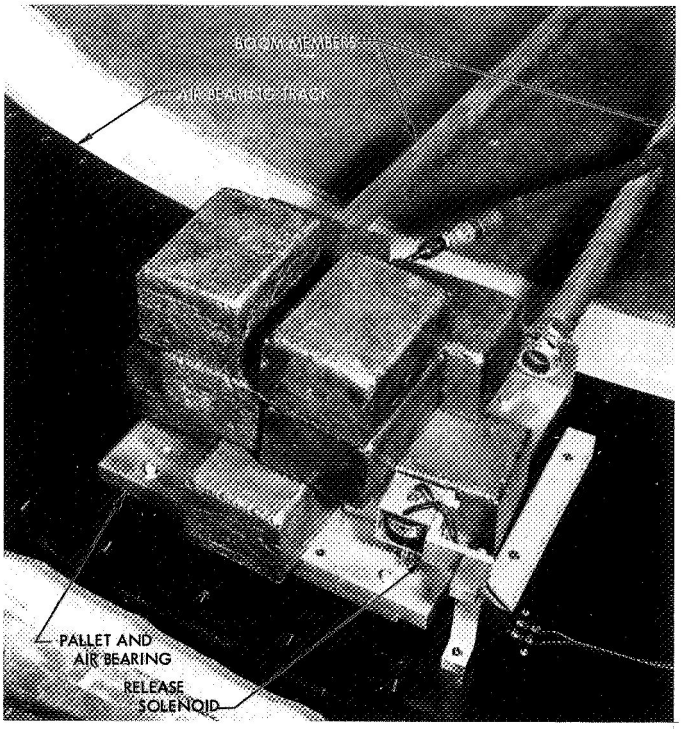

Fig. 3. RTG simulator and air bearing

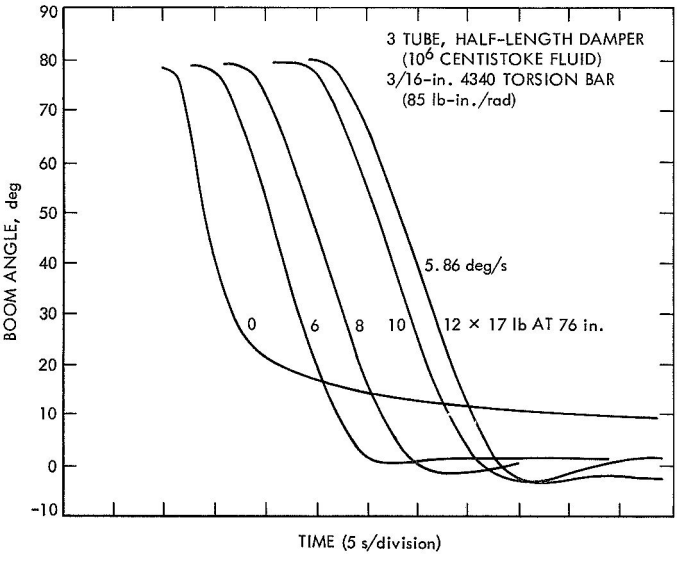

Fig. 4. RTG deployment simulator performance

repeatability of the 3/16-in. torsion rods have not been as great as predicted. Causes for this include: (1) residual friction in hinge bearings and air bearing (coefficient on the order of 3×10^{-4}), (2) preloading of the torsion rod to within 20 deg of its yield point angle, and (3) distortions resulting from heat treating of the steel rod. The latter effects produce a torque–angle relation that appears to be a function of the square of the angle, rather than linear. Figure 4 shows typical angle versus time plots for the steel torsion rod; the peak torque coefficient of 85 in.-lb/rad corresponds to a linear coefficient of roughly 60 in.-lb/rad. The dimensionless relation

$$\frac{T_s}{C_d R_d \dot{\theta}_{\max}}$$

(where T_s is the mean torsion rod coefficient, $C_d R_d$ is the damping torque coefficient, and $\dot{\theta}_{\max}$ is the peak velocity in radians/second) gives an indication of the correspondence between theoretical and experimental systems; for the system performance in Fig. 4, this quantity is 0.69, compared to 0.66 for the theoretical system described in SPS 37-60, Vol. III.

This result is sufficient to conclude that the concentric tube damper–torsion rod actuator is a valid approach to deployment of the high moment of inertia booms on

the TOPS spacecraft. Estimated weight for a flight-type actuator–damper is within the 2.5-lb limit: the entire assembly, including hinge fixtures, compression member, needle bearings, and boom member attachments, is 4.9 lb, while the weight penalty for inclusion of the actuator–damper is only 1.3 lb.

2. Magnetometer Boom Study

a. Introduction. A brief survey of commercially manufactured extensible booms has been conducted to determine if an advance in the state-of-the-art is necessary to meet the requirements for the vector helium magnetometer and plasma wave detector booms on TOPS. Design criteria at present are: 30-ft length; approximately 2-lb end mass; maximum weight of boom element plus deployment mechanism, 13 lb; pointing angle accuracy ±3 deg; residual magnetization less than 0.1 gammas.

b. Depth of study. The available types of long extensible booms were examined for their capability of meeting the above criteria within the following constraints:

(1) Maximum bending strength—the boom must withstand flight accelerations of 0.1 *g* maximum, but additionally should be capable of ground extension with minimum external support.

(2) Torsional pointing accuracy—deflections resulting from deployment, thermal effects, and unsymmetrical acceleration loads should be within the ±3-deg limit.

(3) Thermal distortion—bending due to temperature gradients around the boom circumference should be minimum. Such gradients result from solar heating and the proximity of the RTGs. As part of the study, a computer program has been devised to predict both these effects to a first-order approximation.

(4) Maximum fundamental cantilever vibration frequency.

(5) Minimum micrometeoroid damage or degradation.

(6) Compatibility of materials with the minimum magnetic interference, low temperature, and zero outgassing requirements.

c. Characteristics of tubular boom types. Most of the common types of extensible booms are of preformed tubular metal foil, which is flattened, stored on spools, and deployed either electrically or by stored strain energy. Variations include one, two, or three foil elements, overlapping or interlocked elements, and welded flange types. In general, all suffer from torsional weakness, high thermal distortion due to large cross section and poor circumferential heat transfer, and some minor buckling on repeated cycling.

Achieving the torsional pointing accuracy requires a heavier tubular foil boom: a typical example is the Spar Aerospace Products Bi-Stem (Fig. 5), which would be 2 in. in diameter, 0.010-in. wall, of austenitic stainless steel, with an element weight of 0.4 lb/ft, and total weight of about 21 lb.

d. Triangular truss boom. The torsional and thermal deficiencies of the tubular boom are overcome by the Astromast, a product of Astro-Research Corporation (Fig. 6). A 6-in. boom with 0.15-in.-diameter silverplated epoxy-glass longerons would weigh 0.2 lb/ft, be torsionally rigid when fully deployed, have negligible thermal distortion since no longerons are shadowed, and have a total weight of 15 lb, including a 7-lb deployment mechanism/housing. Its major disadvantage is that cabling is exposed to the space environment, rather than being protected within the tubular boom element.

3. Regenerative Pump for TOPS Fluid Loop

a. Introduction. Active temperature control of science instruments by means of a fluid loop transferring waste heat from the RTG is being contemplated. Present requirements are for a volume flow of 1.2 ml/s (8.7 lb/h) of silicate ester fluid, with a line pressure drop of about 1 psi. Redundant pumps will be carried on the spacecraft, but each should individually be capable of uninterrupted operation during the 100,000+ hour mission with minimum electric power consumption.

Candidate designs for the fluid loop pump fall into three categories: positive displacement, static, and rotary valveless. In general, positive displacement types have contacting moving parts which limit lifetime. The thermomechanical reciprocating pump conceived for the TOPS fluid loop (SPS 37-64, Vol. III, pp. 113–118) shares this fault, but its zero electric power consumption was considered attractive before the flow power requirements were reduced to the present level. Static pumps based on magnetohydrodynamic and ferrofluidic principles have been briefly investigated, but require excessive magnetic field strengths. Of the rotary pumps, centrifugal types

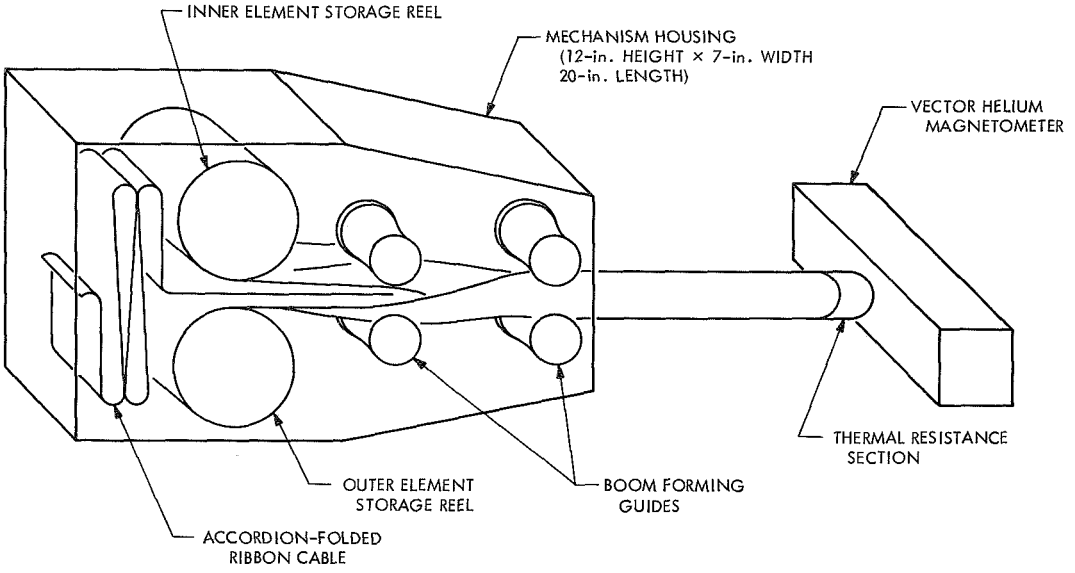

Fig. 5. Two-spool Bi-Stem VHM Boom

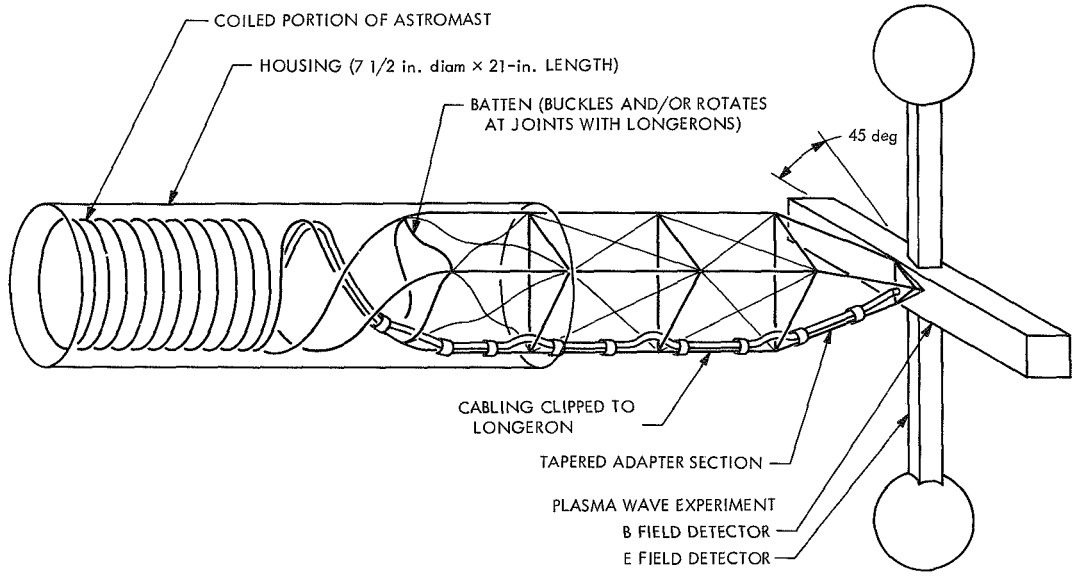

Fig. 6. 30-ft Astromast boom

have diminishing efficiencies at these flow power levels and require high-speed impellers (10,000 rpm up) (Ref. 1).

b. Regenerative pump. The regenerative pump (also known as "peripheral" or drag pump) operates by a combination of centrifugal and viscous effects to produce the required flow and head at very low speeds (300 rpm) with moderate efficiency (up to 10% at 0.1-W flow power). It consists of a vaned rotor and an annular cavity (Fig. 7) with the annulus constricted to minimum clearance between the outlet and inlet ports. Pressure in the outer annulus is built up by synchronized passage of the helical fluid flow through successive rotor vanes. Viscous drag on the fluid causes this induced vortex to follow the rotor until it reaches the outlet cut-off (Ref. 2).

Other advantages of the regenerative pump stem from its simplicity: the impeller can be incorporated into the rotor of a multi-pole hysteresis synchronous motor, thus requiring no penetrations of the fluid loop by shafts or electrical connections (Fig. 8). Only two bearings are required, which operate in the lubricating fluid. There are no axial bearing loads, and radial loads can be minimized by symmetrical placement of two inlet–outlet cut-offs.

c. Test model, procedure, and results. Commercial peripheral pumps with similar flow and head characteristics operate with higher rotor speeds (e.g., 3600 rpm); a test model with a 3-in.-diameter 76-vane rotor was therefore constructed to determine the feasibility of a 300-rpm regenerative pump (Fig. 9). Part of the stator/housing is made of Lucite plastic, to enable observation of the vanes

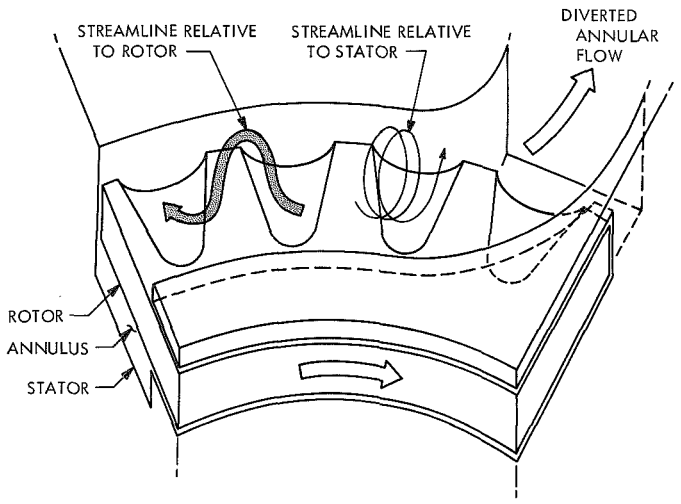

Fig. 7. Theoretical flow patterns of regenerative pump

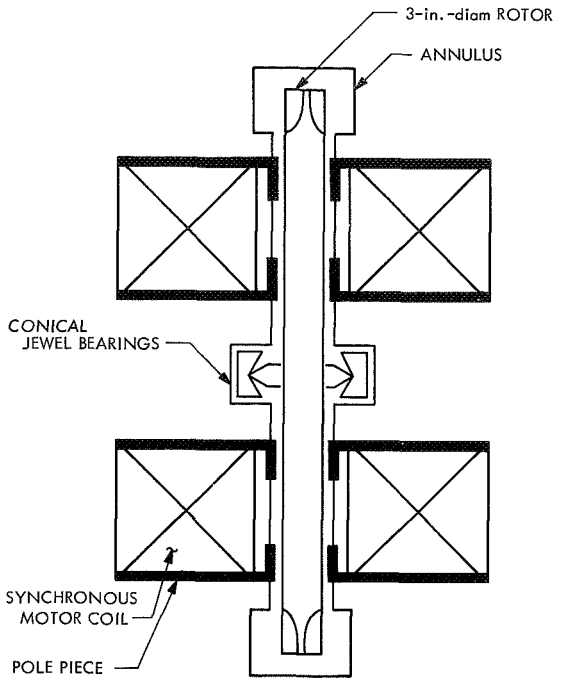

Fig. 8. Integrated pump motor

and annulus through a microscope and prism. The helical streamline pattern is marked either by bubbles entrained in the fluid or by injecting a stream of dye into the annular cavity.

Test runs were made from 180 to 1800 rpm at flow rates of 0.5 and 1.2 ml/s, driving the pump by a variable speed universal motor through a pulley. Other experimental apparatus (Fig. 10) included ammeter and voltmeter for measuring motor input power, oscilloscope and counter for rpm measurements, magnetic sensor for triggering the oscilloscope, counter and a Strobotac used for observing individual vanes, a mercury manometer, a ball-type flowmeter, and a torquemeter mounted on the drive pulley.

Efficiency (flow power/shaft power) and flow power are given in Fig. 11 for Coolanol 45 fluid and rotor speeds of 270 to 1350 rpm. Note that even this preliminary design is capable of producing the desired flow power (0.01 W) with 1.4% efficiency. The increasing efficiency with decreasing speed is not predicted by theory; efforts are now underway to extend the low range of the counter trigger and torquemeter to eliminate the possibility that this results from instrument inaccuracies. The flow power and developed pressure (Fig. 12) are nearly linear from 300 to 1500 rpm, permitting life testing of this type of pump to be accelerated as much as 5 times with easy extrapolation back to the normal operating regime.

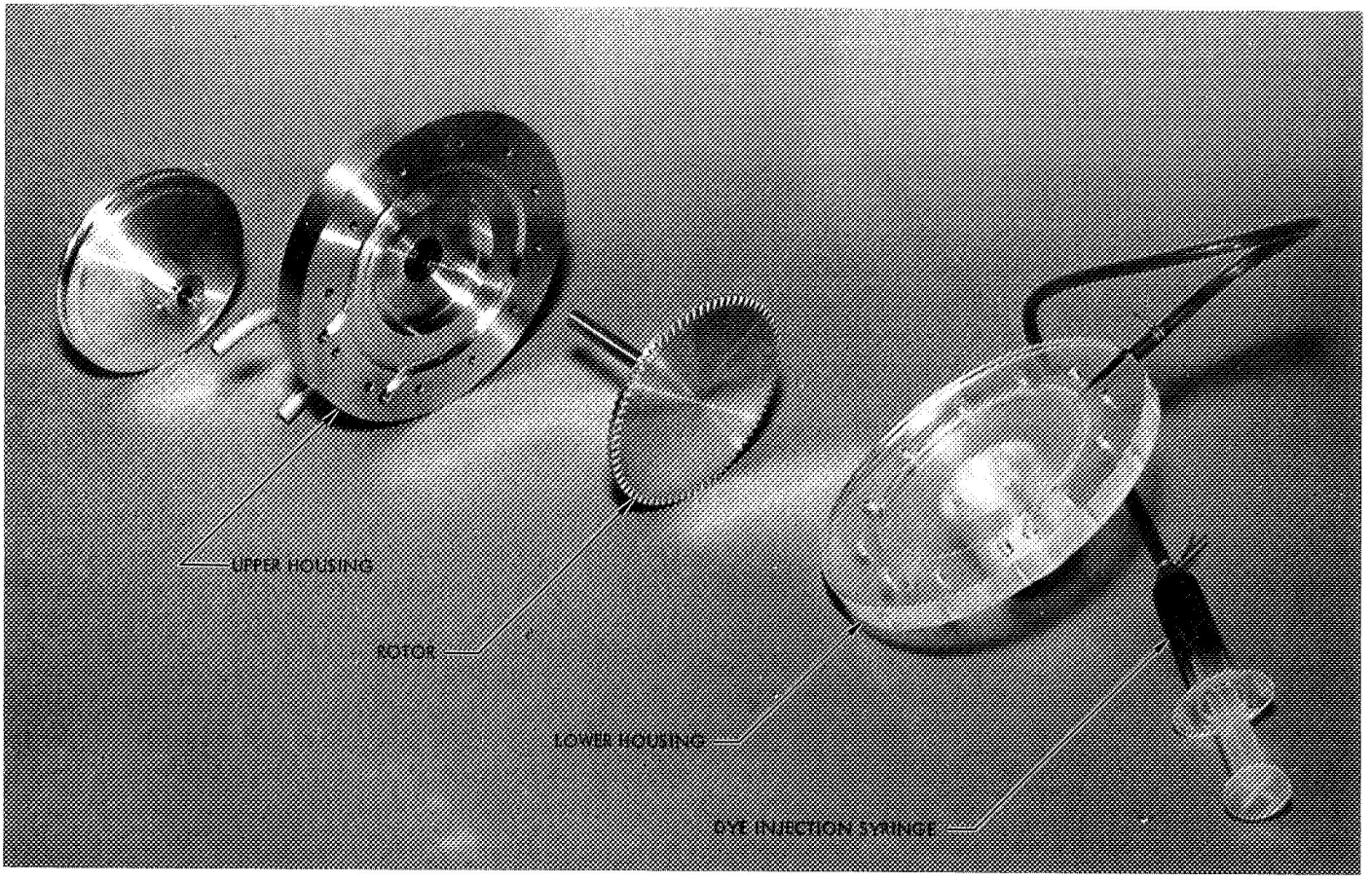

Fig. 9. 3-in.-diam rotor regenerative pump

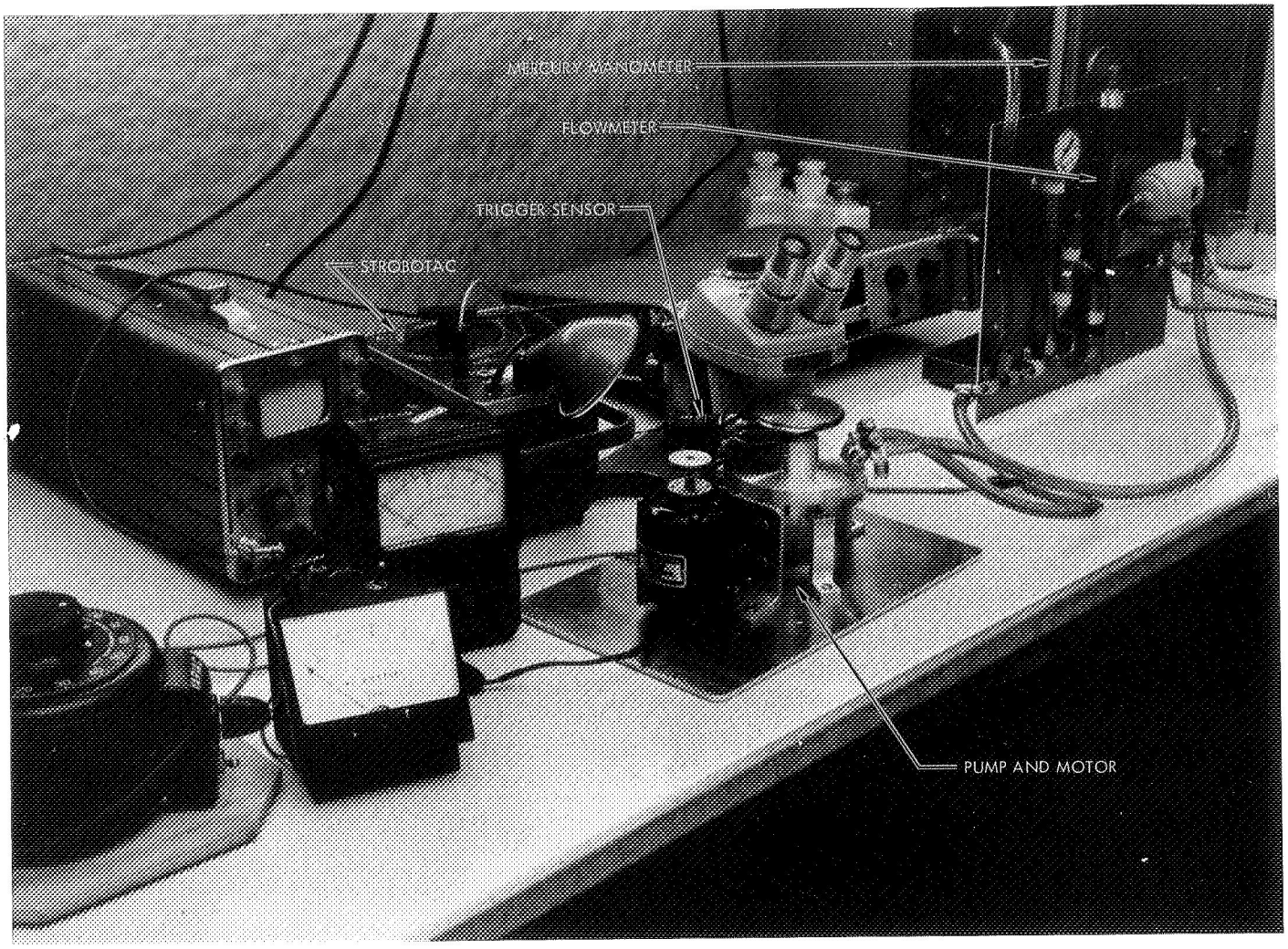

Fig. 10. 3-in.-diam pump in test assembly

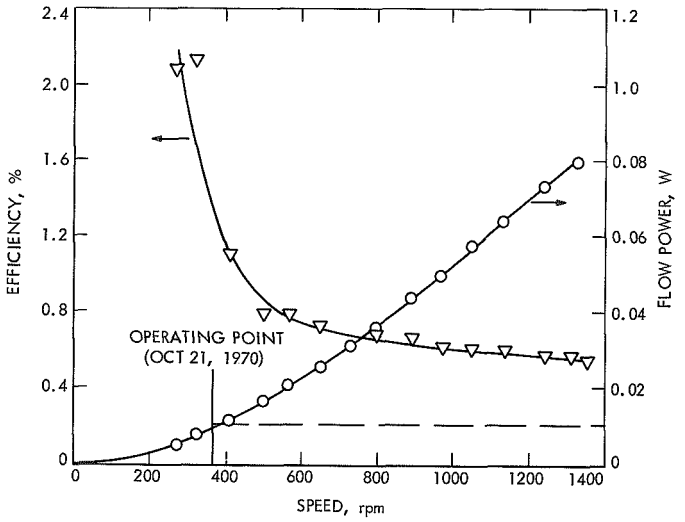

Fig. 11. Efficiency and flow power vs speed (volume flow rate = 1.2 ml/s)

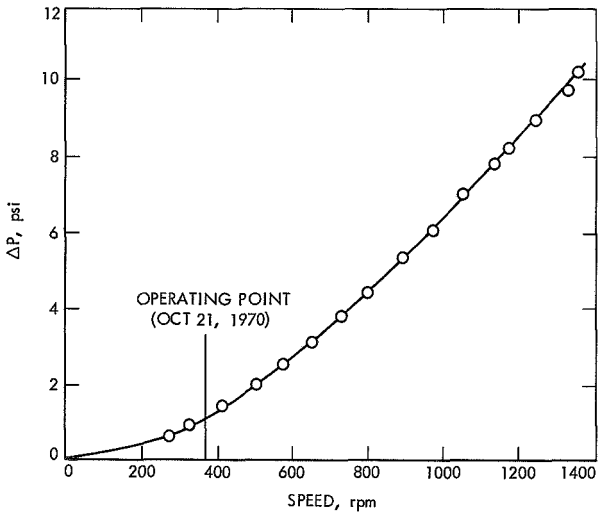

Fig. 12. Pressure ΔP vs speed at constant flow rate (volume flow rate = 1.2 ml/s)

d. Future work. If the efficiency increase is real, it can be expected to peak at 5–10%; a second model of the regenerative pump can be designed to move this peak to the desired flow power and rpm. Alternatives to the regenerative pump are still being investigated; if this type of pump is selected, such an optimized model will be constructed and integrated into a drive motor. Possible types of bearings, and methods of determining bearing wear during accelerated and normal life testing, are being studied in anticipation of initiating such tests.

References

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2. Wilson, W. A., Santalo, M. A., Oelrich, J. A., "A Theory of the Fluid-Dynamic Mechanism of Regenerative Pumps," *Trans. ASME*, Vol. 76, p. 1303, Nov. 1955.

B. TOPS High-Gain Antenna,[1] *D. J. Starkey*

1. Introduction

The TOPS high-gain antenna employs a 4.25-m-diameter deployable main reflector. X-band efficiency requirements imply a necessary surface accuracy of approximately 1 mm rms. This antenna is being developed in-house. Although past articles (SPS 37-65, Vol. III, pp. 47–52, 122–125) have discussed several aspects of this development, this is the first comprehensive article.

2. History

When the TOPS requirement became known, in 1968, JPL conducted a survey of deployable high-gain antennas. Two of these, the Lockheed flexible radial rib and the Convair expandable truss, appeared most promising. Further study, however, indicated that each had certain shortcomings with respect to TOPS.

In June 1969, JPL initiated further study of a concept that had earlier been proposed for *Mariner B*. This is a rigid radial rib/soft mesh design, in which the ribs are hinged to fold up around the cassegrainian subreflector for stowage. Although this design lacks the packaging efficiency of other concepts, it appeared more straightforward and thus more likely to meet the surface accuracy requirement.

Ideally, the rib and mesh antenna would approximate the desired paraboloid by forming parabolic cylinder elements. In fact, the radial mesh tension that is necessary to prevent circumferential wrinkling of the mesh causes it to bow inward, increasing this inherent geometric error. At the time of this design study, JPL was already working with computer programs for determining geometric errors and for assessing the effects of surface errors on antenna gain.

Recognizing that the hub had to be fairly large to accommodate the hinge points around its periphery and to provide access for the feed horn, and in the belief that doing this would tend to minimize the total rms surface error, the hub diameter was made the maximum that could be accommodated on TOPS, 1.4 m. This provides for a relatively large fixed center section and short ribs. Geometric error analysis then gave a minimum required rib number of 42; a 48-rib design was chosen somewhat arbitrarily. Preliminary layouts of the antenna were completed in September 1969.

The project status was reviewed in January 1970. This included assessment of the impact of further deployable antenna developments by industry. The conclusion was that the TOPS project objectives could best be met by continuing the in-house development of the radial rib antenna.

3. Design and Fabrication

The major design parameters for the TOPS high-gain antenna reflector are as follows:

Type: radial rib/mesh deployable

Deployed diameter: 4.25 m

Focal length/diameter: 0.415

Surface accuracy: 0.89 mm rms

Stowed envelope: cylindrical, 1.4-m diameter × 2.0 m

Weight (flight design goal): 15 kg

Figure 1 shows the mockup that was constructed as a part of the TOPS full-scale spacecraft model.

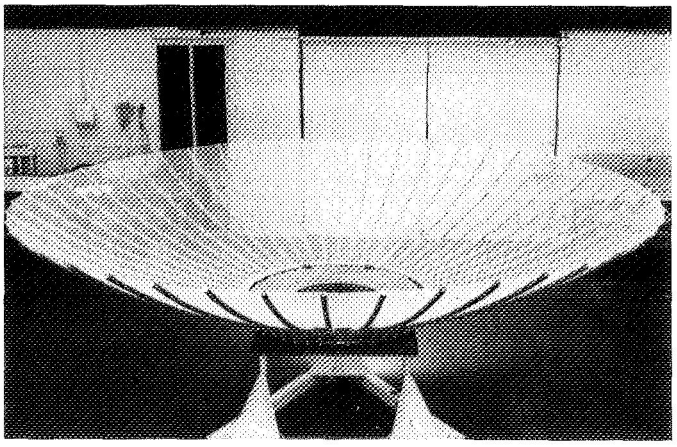

Fig. 1. TOPS high-gain antenna mockup

[1]In the course of this work, Radiation, Inc., disclosed to JPL that they have developed a very similar deployable rib/mesh antenna. It was designed for use with a focal point feed and incorporates a central deployment mechanism that is incompatible with the JPL cassegrainian feed. However, their experimental results served to greatly increase JPL's confidence in the correctness of the approach and the attainability of the TOPS objectives. Also, Lockheed and Convair designs have evolved; both companies have delivered antennas to NASA, so some of JPL's earlier concerns may no longer be valid.

The hub (Fig. 2) is a torus, of triangular cross section. It consists of "pork chop" stiffeners (Fig. 3), each having an integral rib hinge half, interconnected by sheet metal plates. To avoid increased fabrication costs, the development model hub was made overweight with respect to the flight design. However, this was done consistently, such that structural test results will give an accurate indication of the capabilities of the latter. The material is 6061-T6 aluminum alloy.

The rib material is 6061-T6 aluminum alloy tubing. The rib diameter tapers uniformly from 2.8 cm at the root to 0.9 cm at the tip, while the wall thickness varies from 0.5 to 0.4 mm over the same interval. The rib assembly consists of the following items, all adhesively bonded together: rib, T-section trim strip, rib extension, and elbow fitting (containing the other hinge half). The planned strategy is to bend the ribs to an approximately correct contour and then meet the close tolerance requirement by final machining of the trim strip. The rib will be accurately positioned with respect to the hub by line drilling of the hinge pin hole, using appropriate tooling. A stop on the rib extension, which bears against the "pork chop" stiffener, provides for adjustment of the deployed rib position. In contrast with the hub, the ribs are of substantially flight design, since there is much to be learned about their fabrication and properties.

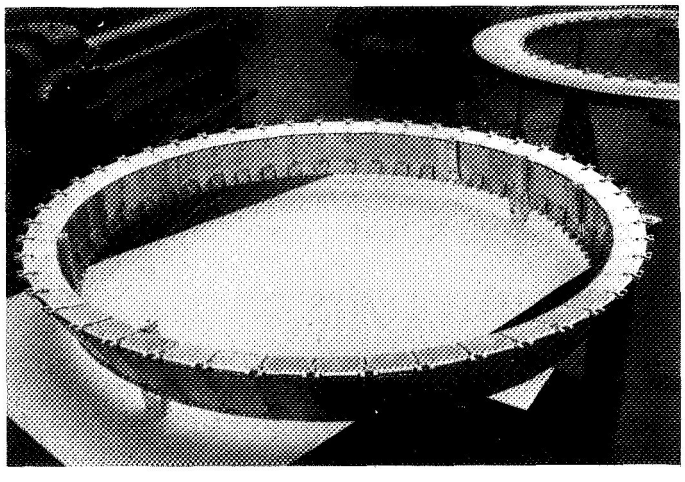

Fig. 2. TOPS high-gain antenna hub

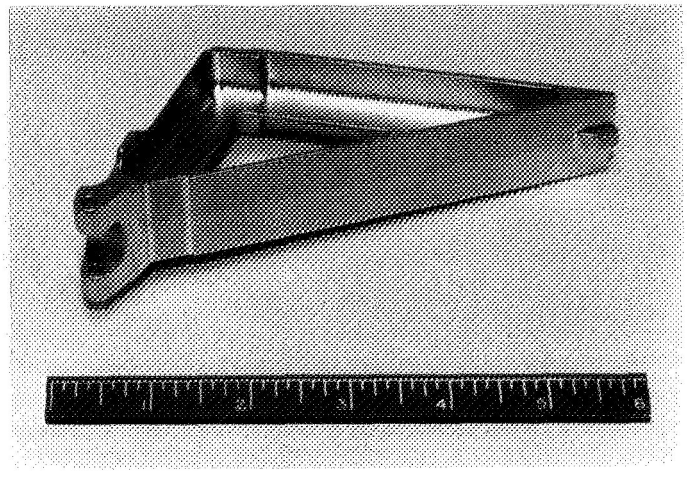

Fig. 3. TOPS high-gain antenna stiffeners

The optimum deployed rib shape is calculated with a program which first computes the shape assumed by a mesh surface attached to parabolic ribs and then optimizes the rib shape so as to minimize the rms surface error with respect to the desired paraboloid. The as-manufactured (relaxed) rib shape is then obtained by introducing the elastic properties of the rib. A thermal offset could also be included, if it were desired to design for minimum surface error at other than the manufacturing temperature, but this was not done for the development model. The rationale is that most of the testing will be done at room temperature and that this would introduce needless complexity.

The deployment mechanism is one area wherein it is felt that the present design is less than completely satisfactory. The requirement for penetrating the center of the dish with the feed horn and its waveguide connection effectively precludes use of central deployment mechanisms which would otherwise be attractive. The present design accomplishes deployment by means of redundant Negator springs attached to the rib extensions and operating from drums contained within the hub. Pending the development of compact, reliable rib deployment rate control devices, the springs must be carefully sized with respect to the deployment environment, such that the ribs do not impact the stops with sufficient angular velocity to cause damage.

The mesh that will be used on the TOPS antenna is a rather standard one for deployables; a tricot knit, Chromel-R material having approximately 5 strands per lineal cm. It is electroless gold-plated for improved RF reflectance. While there is some concern regarding the brittleness and relatively poor adhesion of the plating relative to a long-duration outer planet mission, and efforts are being made to develop a better material, it is adequate for the development model antenna.

The strategy that is presently contemplated for fabrication and installation of the mesh surface is to stretch the

material under the proper tensions, outline the gores with glass tape (which ensures subsequent stability of the edge dimensions), and cut them out. The gores would then be machine-sewn to form the complete "skirt" and this would be attached to the ribs by sewing through holes in the T-section. This technique (except for differences in rib attachment) was used in the construction of the model previously mentioned, and worked well.

Temperature control considerations were included in the design of the hub and the rib. The present plan is to insulate the hub so as to minimize gradients therein and to provide the ribs with a grey-body finish to ensure predictability and long-term stability of properties. Preliminary rib temperatures and gradients for several points along the TOPS trajectory have been calculated, but, because of resource limitations, their total effects on surface distortion and focal point location have not yet been determined.

4. Development Status

The hub is completed; other parts (except the central dish) are either on-hand or on order. Ways of reducing the estimated cost of the central dish are being investigated prior to ordering this item. Rib assembly and final machining is expected to be a pacing item. Completion is scheduled for June 1971.

Current tasks include: experiments in fabrication and assembly techniques, determination of mesh properties, thermal distortion analysis, development of a rib deployment rate control device, and the development of a superstructure capable of carrying the launch loads imposed by the subdish and other spacecraft equipment mounted to it, and which does not cause excessive RF blockage losses.

5. Planned Tests

Mechanical tests will include static surface accuracy, deployment repeatability, and simulated 0-g measurements. Although it would be desirable to perform thermal-vacuum tests, presently envisioned TOPS resources do not permit this, and alternate methods of confirming thermal distortion analyses are being sought.

The Telecommunications Division has developed the TOPS antenna feed and will perform RF testing.